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published in
Current opinion in psychology
2019

DOI (link to publisher)
10.1016/j.copsyc.2018.12.024

document version
Publisher's PDF, also known as Version of record

document license
Article 25fa Dutch Copyright Act

Link to publication in VU Research Portal

citation for published version (APA)
Theeuwes, J. (2019). Goal-driven, stimulus-driven, and history-driven selection. *Current opinion in psychology*, *29*, 97-101. https://doi.org/10.1016/j.copsyc.2018.12.024

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Current Opinion in Psychology

Goal-driven, stimulus-driven, and history-driven selection

Jan Theeuwes

In this paper, I present a framework which considers three independent factors that drive attentional selection. In addition to goal-driven and stimulus-driven selection, I discuss how lingering biases of selection history play a major role in attentional selection. Visual statistical learning of the regularities in the environment forms the basis for this history-based selection which provides an elaborate and flexible attentional biasing mechanism above and beyond goal-driven and stimulus-driven factors. A selection based on experience and history is fast, automatic and occurs without much, if any, effort. I conclude that learning and extracting the distributional properties of the environment have a major impact on attentional selection.

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Current Opinion in Psychology 2019, **29**:97–101

This review comes from a themed issue on **Attention and perception**

Edited by **Sarah Shomstein**, **Andrew Leber** and **Joy Geng**

For a complete overview see the Issue and the Editorial

Available online 7th January 2019

https://doi.org/10.1016/j.copsyc.2018.12.024

Introduction

In everyday life, we try to focus our attention to those events that are relevant to us and ignore information that could distract us. For example, when driving along a busy road, we devote attention to traffic signs, road users, and to locations in between parked cars searching for potential 'targets' such as children who may want to cross the road. In the meantime, we try to ignore the buzzer of our phone, the blinking light telling that you are almost out of gas, and the visually loud billboards placed along the road. The overload in input necessitates filtering and attenuation, allowing some information to be prioritized over other [1].

Traditionally, attentional selection was considered to be the result of the interaction between the goals of the observer (current selection goals) and the physical properties of the visual environment (salience of the objects) [2–4]. Recently, however we [5–7] pointed out that in many instances selection is neither the result of goals of the observer nor the result of stimulus-driven factors (i.e. bottom–up saliency). A third category of selection was suggested, which we labelled 'selection history' referring to the notion that previous attentional deployments can elicit lingering and enduring selection biases that are unrelated to the current goals nor related to the stimulus-driven saliency of objects [7]. This notion of 'selection history' as an important driver of attentional selection is shared many others (see also Refs. [8–10]), even though in previous studies these effects may have been falsely labelled as being 'top–down', ([11] for a discussion see Ref. [12]).

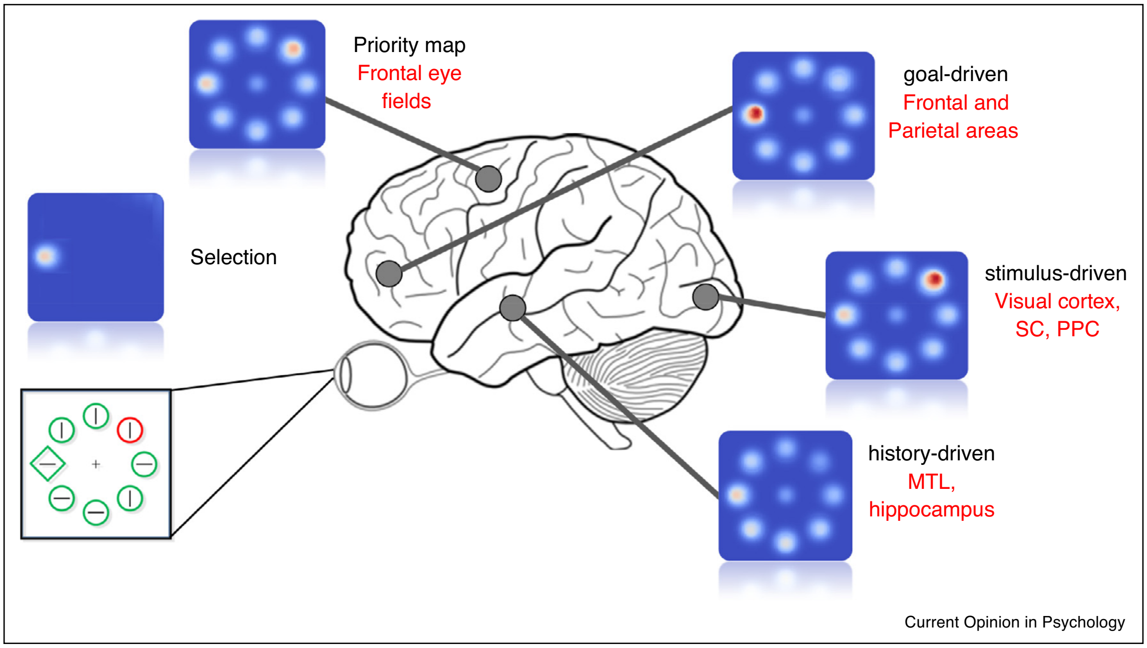
Priority map: stimulus-driven, goal-driven, and history-driven factors

Current goals, physical salience, and selection history (see Figure 1) all feed into an integrated *priority map* which represents a conceptual framework accounting for selection priority. The priority map is assumed to be a winner-take-all neural mechanism that guides the allocation of covert and overt attention [2,13]. It is reasonable to assume that at any moment in time these three factors (goal-driven, stimulus-driven, and history-driven effects) determine the weights within the spatial priority map. Within this map, the weights are combined into a single topographic representation of the environment, which determines the selection priority (e.g. which location is selected first, second, third etc.). As noted, individual signals acting on the priority map originate from sensory input (bottom–up), current goal states (top–down, or behavioral relevance) and lingering selection biases (history driven). At any given time, these priority signals compete with one another. For example, the well-known attentional capture effect is a demonstration that bottom–up salience signals may be so strong that they overshadow (at least initially) goal-driven selection [7,14–16]. Figure 1 gives an overview of the likely brain regions that are involved in generating these signals. There are many cortical areas identified as candidate spatial priority maps including the posterior parietal [17,18] and frontal cortex [13,19].

Stimulus-driven selection

In its most extreme definition stimulus-driven selection (or bottom–up attention) refers to a situation in which the control of attention lies outside the organism: as soon as a particular stimulus is presented, attention is directed to it. Posner [20] called this 'exogenous attention' and referred to it in terms of a physiological reflex. Research has shown that this extreme view is not correct: by focusing attention in a top–down way to a particular location in space, stimuli

Figure 1



Simplified overview of the different factors and presumed brain regions involved in attentional selection. The priority map emerges from a distributed network involving frontal, partial, temporal areas. Goal-driven selection comes from frontal areas (including anterior cingulate); Stimulus-driven bottom–up selection could come from early visual areas and structures like the superior colliculus [2]. Selection history (statistical learning) is assumed to be represented at MTL (including hippocampus). These three signals feed into the priority map (possibly within the FEF [60]) which ultimately determines selection (figure adapted from [61]).

that are known to capture attention (such as abrupt onsets) can be fully ignored [21–23]. Even though these findings indicate that some control is possible, it is generally agreed that stimuli that stand out from their environment have the ability to capture covert attention [14,15] and overt attention [24,25]. Several computational models have stressed the role of salience in attentional selection [2,26]. These models take an image as input and process the image in parallel across various feature channels using different spatial scales. The end result is a set of topographic feature maps which are then combined into a priority map coding selection priority in in terms of salience (i.e. saliency map) [2]. There are several candidate brain areas that could serve as maps of saliency. For example, the frontal eye field (FEF) [27], the lateral intraparietal area (LIP) [18], the superior colliculus [28], and the substantia nigra [29].

Goal-driven selection

Goal-driven selection, often called top–down attention, is more difficult to define than stimulus-driven selection. Some claim that any selection that is not stimulus-driven (bottom–up) must be controlled from 'the inside', that is in a top–down way [30]. Many use very broad categories for top–down control referring to selection that is influenced by 'context, learning, or expectation' [31]. Others have stressed the aspect of volitional control. For example, some claimed that "*Top–down visual attention is a voluntary process in which a particular location, feature, or object relevant to current behavioral goals is selected internally and focused upon*" (p. 515 in Ref. [32]) and "*volitional top–down process, which can exert its influence through acts of will*" (p. 210 in Ref. [33]). It has also been argued that attention can be guided in a top–down way even when guidance is involuntary and inconsistent with goals and task set of the observer [30,31]. Regardless of the exact definition of goal-directed top–down control (see Refs. [30,31,34,35] for a discussion), it is important to distinguish between selection based on intentional, moment-to-moment, volitional control (such as "I direct my attention to the right side of the visual field, and on the next trial to the left side of the visual field") from selection that is driven by previous selection episode (i.e. selection history [5,7]). When this distinction is made, it is possible to study the separate contributions and interactions of stimulus-driven, goal-driven, and history-driven selection.

History-driven selection

Whenever attentional selection is driven by experiences with previous selection episode one speaks about 'history-driven selection' [5,7]. It is crucial to realize that objects can become prioritized in attentional selection due to selection history even when these objects are not salient (i.e. constitute no strong bottom–up signal) and even when these objects are completely irrelevant for the task at hand (i.e. constitute no top–down signal). There are several instances of how previous experiences affect attentional selection.

Firstly, reward tied to a stimulus affects attentional selection even if the stimulus no longer predicts reward delivery (see Ref. [6] for a review). These studies typically have two phases. During training, the successful selection of the target is rewarded, resulting in a reward association for the specific visual feature of the target. During the test phase, participants search for a different target and no rewards are delivered. The results show that previously rewarded stimulus — even when the stimulus is non-salient — captures attention and interferes for search for the target. These results are well established both in covert [37–40] and overt search [41,42].

Secondly, another well documented phenomenon of selection history affecting current selection episodes is 'priming', which describes how a stimulus (feature) that has been repeatedly attended in the past is more efficiently selected and identified on the current trial [43]. Priming is well-documented in terms of its low-level facilitatory effect on perceptual processing [43,44]. Maljkovic and Nakayama [43], for example, demonstrated the influence of priming in the context of a search task. Priming between trials, or intertrial priming, occurred for up to eight successive trials, even when participants were unware of repetitions [45], or when they were informed that the target was unlikely to be same between trials [45].

Thirdly, participants seem to learn statistical regularities present in the environment which in turn biases attentional selection [46]. For example, research known under the term 'contextual cueing' has shown that search for a target is facilitated when it appears in a visual lay-out that was previously searched relative to visual lay-outs that were never searched before [47,48]; for a review see Ref. [48]. In the classic paradigm, participants are instructed to search for a 'T' target among 'L' distractors in sparsely scattered configurations. Half of the display configurations are repeated across blocks while others were only seen once. The basic finding is that participants are faster in finding targets when they appeared in repeated configurations, suggesting that participants have learned the association between the spatial configuration and the target location. Recently, it was shown that people not only learn the statistical regularities regarding the target but also regularities about the distractor, which in principle are irrelevant for the task and not part of goal-driven search [50–53]. Wang and Theeuwes [51–54] used the well-established additional singleton task [14,15] and independently manipulated the distributional properties of the distractor. They demonstrated that when a distractor appeared more often in one location than in all other locations, its distracting effect (the extent to which it captured attention) was reduced. Moreover, if the target happened to be presented at this location, selection of the target was less efficient. There was also a gradient of spatial suppression around this location, suggesting that this location competed less for attention than all other locations. Wang and Theeuwes [51] interpreted these findings as evidence that statistical regularities can bias attention such that within the attentional priority map, the location that is likely to contain a distractor singleton is suppressed relative to all other locations.

It is likely that priming and reward learning are special cases of the overarching mechanism of visual statistical learning (i.e. selection history [8]). There is ample evidence that statistical learning takes place even though most participants are not aware of the regularities in the environment [36,47–49,51,54]. Statistical learning (history-driven selection) is fast, automatic, flexible and occurs without much, if any, effort [7] and it is likely that its effect on visual selection is large and much more ubiquitous than previously assumed.

It is generally accepted that the medial temporal lobe (MTL), and in particular the hippocampus, is critical for the rapid extraction of regularities from the environment [55–57]. The MTL has been known to play a crucial role in the representation of space, and particularly allocentric spatial location as demonstrated by the discovery of 'place cells' in both rodents [58] and humans [59]. The assumption is that activity in the MTL represents associations between spatial and object regularities in the environment [55]. This activity pattern is then fed back to the priority map affecting visual selection.

Conclusions

The outline discussed provides a novel framework to study visual selection. The framework provides a context to study how these signals (goal-driven, stimulus-driven and history-driven) act on the spatial priority map, how they interact, and in which time windows they operate. For example, it is possible that history-based statistical learning drives attention to one location in space, even when observers effortfully in a goal-driven way try to direct attention to another location. Wang and Theeuwes have shown that history-driven effects can attenuate attentional capture by salient singletons [50–52]; yet it is unknown whether history-driven effects can completely eliminate attentional capture, as was previously shown for top-down directed attention [21,22].

Conflict of interest statement

Nothing declared.

Acknowledgement

This work was supported by an ERC advanced grant under grant number ERC-2012-AdG – 323413 awarded to Jan Theeuwes.

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